EJFA Emirates Journal of Food and Agriculture

Emirates Journal of Food and Agriculture 36: 1–9
doi: 10.3897/ejfa.2024.119905

RESEARCH PAPER

Investigating the synergistic impact of ozonated water irrigation and organic fertilization on tomato growth

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Academic editor: Abdul Jaleel ♦ **Received** 31 January 2024 ♦ **Accepted** 21 February 2024 ♦ **Published** 14 March 2024

Abstract

This study presents the outcomes of an experimental investigation aimed at evaluating the combined impact of irrigating tomatoes with ozonated water and applying organic fertilization. The experiment was conducted in a greenhouse equipped with an innovative ozonated water generation system. Tomato seeds were planted in 240 pots of 2-liter volume, arranged in 16 rows with 15 pots each. Alongside the native greenhouse topsoil, three distinct substrate mixtures incorporating compost compositions of 10%, 20%, and 40% were examined. Regular irrigation, twice a week, was implemented using three varying concentrations of dissolved ozone in water (1, 2, and 3 ppm). Results obtained after approximately three months of cultivation unveiled an almost twofold increase in plant productivity with ozonated water irrigation. This effect was notably pronounced when utilizing the native topsoil and a substrate containing 10% compost, coupled with an ozone concentration of 2 ppm. Intriguingly, the use of ozonated water facilitated enhanced development of both aerial and root components of the tomato plants. Moreover, the study suggests that organic fertilization may not be necessary when irrigating with ozonated water, as comparable productivity was observed for both fertilized and non-fertilized soil substrates. Although physicochemical analyses indicated minimal alterations, the noticeable improvement in plant vitality underscores the positive influence of ozone.

Keywords

Irrigation; ozonated water; organic fertilization; compost; agriculture; tomato

Introduction

Irrigation and fertilization are fundamental pillars of agriculture, playing crucial roles in maximizing crop yields and promoting plant growth. Conventional methods, however, face increasing challenges regarding water scarcity and environmental sustainability. This necessitates exploration of innovative and eco-friendly alternatives.

Ozone-infused water irrigation has emerged as a promising technique holding substantial potential for both pathogen control and plant growth enhancement. Ozone's powerful oxidizing properties enable it to combat harmful microorganisms while stimulating crop development, as demonstrated in prior studies on broccoli (Flores et al. 2019) and tomatoes (Díaz-López et al. 2024). Additionally, Pandiselvam et al. (2020) highlighted the impact of ozone treatment on seed germination, emphasizing its potential for enhancing early plant development. Furthermore, Premjit et al. (2022) provided comprehensive insights into the chemistry, physiochemical properties, microbial inactivation, and factors influencing the antimicrobial effectiveness of aqueous ozone, emphasizing its applications in food safety.

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Dielectric barrier discharge (DBD) reactors offer a clean and efficient method for ozone production by converting atmospheric oxygen into ozone via electrical discharge. This environmentally friendly approach makes DBD reactors ideal ozone sources for agricultural applications like irrigation and water treatment, as demonstrated by the research of Draou et al. (2019). Kanfra et al. (2021) investigated the efficacy of electrolytically generated ozone water, produced using diamond-coated electrodes, in controlling phytonematodes in replanted soil, highlighting its potential for soilborne pest management.

Similarly, the adoption of organic fertilization has gained significant traction due to its well-documented advantages for soil health and environmental sustainability. The application of compost and other organic matter sources has been shown to improve soil fertility and enhance crop growth, as observed in tomato studies by Laxmi et al. (2015) and Islam et al. (2017). Furthermore, Gu et al. (2021) investigated the synergic effect of microorganisms and colloidal biochar-based organic fertilizer on tomato growth, underscoring the importance of organic fertilization in optimizing plant performance.

Despite the individual benefits of these techniques, the combined effect of ozone-infused water irrigation and organic fertilization on tomato growth remains largely unexplored. Understanding the synergistic interaction between these methods is crucial for developing sustainable agricultural practices and optimizing crop yields.

Therefore, the present study aims to investigate the combined impact of ozone-infused water irrigation and organic fertilization on tomato growth performance. Our experimental approach will evaluate the effects of various ozone concentrations in irrigation water and compost-enriched substrates on tomato plant productivity. The findings of this study will offer valuable insights for researchers and farmers seeking to implement innovative and environmentally responsible agricultural practices.

Materials and methods

The experimental setting was within a 240 m^2 agricultural nursery situated in "Tabia," approximately 30 km from Sidi-Bel-Abbes city. This facility, managed by the Sodea Hasnaoui company specializing in agricultural development, boasted a meticulously designed greenhouse equipped with an efficient aeration system facilitated by an airflow fan. Detailed specifications of the greenhouse's layout, including environmental controls and stringent phytosanitary measures, were provided to ensure the experiment's reproducibility and mitigate potential environmental biases.

In the second week of February, tomato seeds were sown and later transplanted into the greenhouse. The trial comprised 240 juvenile tomato plants distributed in 16 rows, each row containing 15 pots with a capacity of 2 liters (see Fig. 1). Maintaining row and pot spacing at 0.5 m and 0.3 m, respectively, ensured uniform plant distribution, minimizing spatial effects. Furthermore, to assess their impact on plant growth, three distinct substrate mixtures were employed, incorporating varying compost compositions of 10%, 20%, and 40%.

The selection of substrates and organic compound compositions in our study was guided by specific criteria aimed at evaluating their potential impact on tomato growth. Various factors, including nutrient content, water retention capacity, and microbial activity, were considered in selecting the substrates. The compost compositions of 10%, 20%, and 40% were chosen based on their varying levels of organic matter and nutrient content, with the aim of investigating the dose-response relationship between compost concentration and tomato growth. Additionally, the substrates were selected to represent a range of soil textures, ensuring the inclusion of both sandy and loamy soils to assess their respective effects on plant development. Organic compounds such as composted animal manure, plant residues, and biochar were incorporated into the substrates to provide essential nutrients and support.

The ozone generation system utilized in our study featured a dielectric barrier discharge ozone generator reactor. This reactor was powered by a voltage of 7 kV at a frequency of 20 kHz, facilitating efficient ozone production with an output rate of 10 g/h while consuming 120 W of power.

Regarding the application process, ozonated water was introduced into a 100-liter water tank equipped with a disc-shaped ozone diffuser. An air compressor, optimized for a flow rate of 15 l/min, was utilized to introduce ozone into the water. Regular irrigation sessions were conducted twice a week to ensure optimal soil moisture levels, with each pot receiving a consistent volume of 0.7 liters of ozonated water.

Additionally, a parallel tank containing untreated water was used to irrigate control pots, allowing for meaningful comparisons between treated and untreated groups. To ensure the validity of our experimental results, comprehensive control measures were implemented. These measures included a preventive and curative treatment program to monitor and manage phytosanitary conditions, as well as a fundamental foliar fertilization program aimed at providing essential nutrients to the plants. Rigorous monitoring of environmental conditions and regular data collection were conducted to accurately track plant growth and assess treatment effects reliably.

Physicochemical properties of soil

Soil samples were collected using a randomized design from three points within the field: the central point and its two corners, extracted at a depth of 25 cm (Stolbovoy et al. 2005). A composite sample weighing 1 kg was created by combining subsamples from each point (Rowell 1994). Prior to analysis, the composite samples were air-dried, crushed, and sieved at 2 mm to achieve uniformity (Hendershot et al. 2008). The processed soil samples were then sealed in plastic bags and transported to the laboratory for analysis.

Analysis of soil fertility indicators

Established standard procedures were followed to determine key soil fertility indicators (Sparks et al. 1996). These analyses provided crucial information for understanding soil health and potential productivity.

Particle size analysis

Particle size analysis was conducted using the Robinson pipette method (Gee and Bauder 1986) to determine the proportions of clay, silt, and sand fractions (Day 1965). This analysis helped classify soil texture using the conventional textural triangle (Stolbovoy et al. 2005). Understanding soil texture provides valuable insights into the physical structure and its implications for plant growth and development (Brady et al. 2008).

Statistical analysis

Data obtained from the experiment were subjected to rigorous statistical analysis to evaluate the effects of substrate composition and ozone irrigation on plant growth parameters. Specifically, analysis of variance (ANOVA) was employed to assess the overall significance of differences among treatment groups, followed by the Tukey test for multiple comparisons to identify specific group differences. The significance level was set at $p < 0.05$.

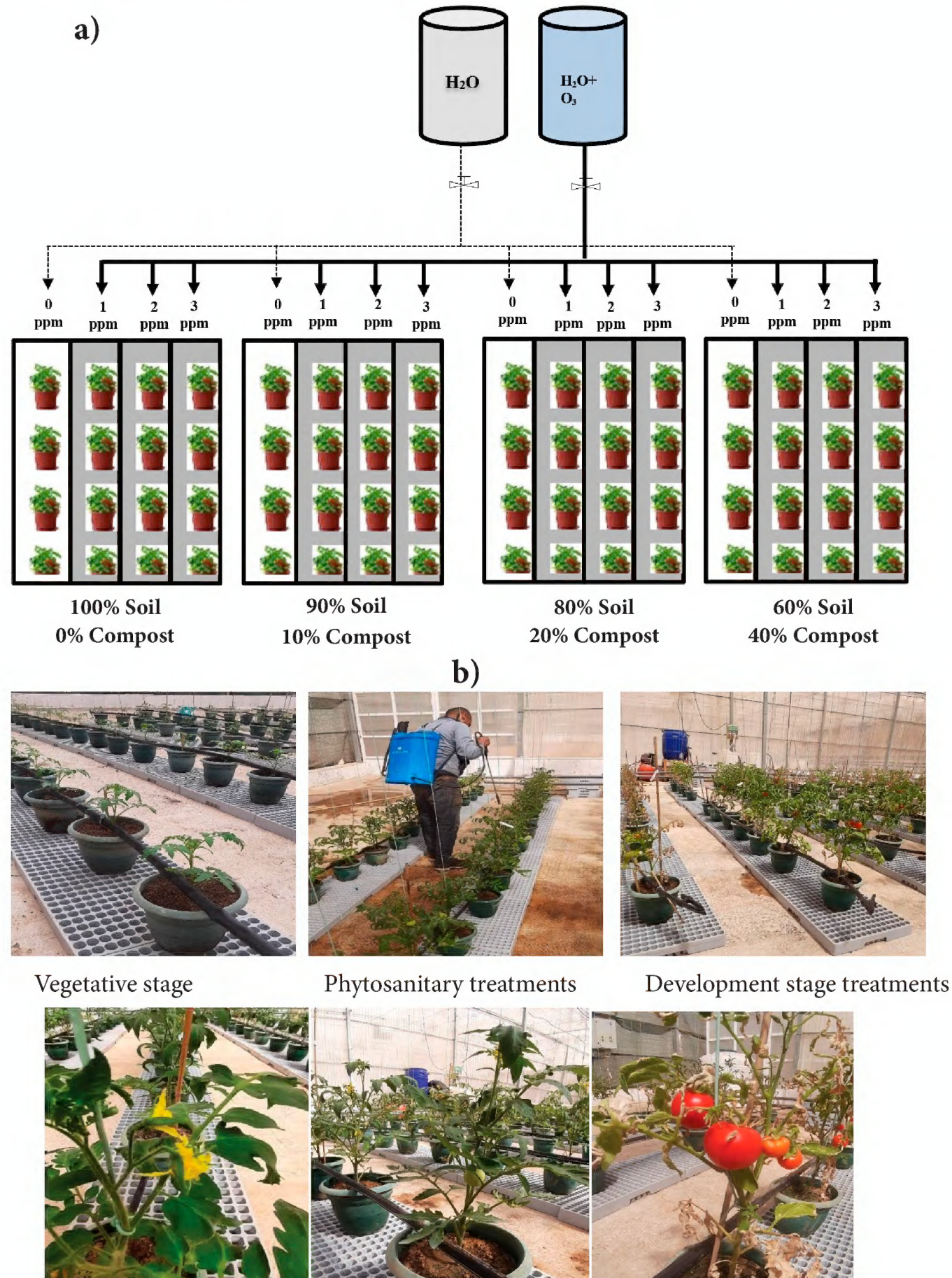

Figure 1. The experimental setup, a) Descriptive schematic b) Successive stages of the experimental study.

Results and discussion

Physicochemical characteristics of the soil

The results of the granulometric and physicochemical analysis are indicated in Table 1, in which information on the soil texture was inherent to each stratum, whose depth of 25 cm was deduced using the soil texture triangle reported by Mathieu and Pieltain (1998).

Table 1. Results of physicochemical analysis of the studied soil.

Parameters		Reference Method	Results
Humidity content		NF ISO 11465	9.26%
pH 'KCL'		NA 751/1990	7.84
Cation exchange capacity (CFC)		NF X31-130/12-1999	10.52 meq/100 gr
Mineral composition			
Exchangeable potassium oxide		ISO 11260/09-2011	4.64 mg/kg
exchangeable Sodium		//	3.55 meq /100 g
exchangeable Calcium		Gravimetry	33.0 meq /100 g
exchangeable Magnesium		//	0.90 meq /100 g
exchangeable Phosphorus		Olsen Method	22.80 mg/kg
exchangeable total Nitrogen		NF ISO 13878/1994	60.0 mg/kg
Ammoniacal nitrogen		//	26.0 mg/100 g
Nitrate nitrogen		//	34.0 mg/100 g
Organic matter		Walkley method	3.35%
Total Carbon		//	3.87%
Total Limestone		Titrimetry	11.04%
Active limestone		Titrimetry	4.20%
Carbon nitrogen ratio C/N			11.38
Granulometry:			
	Sand	ISO 11277 :2020	44.60%
	Silt	/	44.10%
	Caly	/	11.30%
Permeability			Moderate
Textures			Average

Evolution of the plants

The progress of the plants was closely monitored by selecting five pots randomly from each row and recording essential parameters such as the length of the aerial part above the earth (L_{AIR}), the thickness of the plant stem (e), and the number of leaves (N_{LEA}). As illustrated in Fig. 2, the trend in stem length evolution reveals a gradual pattern, characterized by initial slow growth during the first 3 weeks, followed by a more rapid increase.

Significantly, the utilization of enriched substrate (10%) yielded superior results, supported by statistical analyses. The ANOVA test revealed a significant difference among treatment groups (p-value = 0.041), with plants in the enriched substrate group exhibiting a mean stem length of 37 cm by the conclusion of week 10, surpassing the approximately 32 cm observed for the unenriched substrate. This notable enhancement can be attributed to the heightened nutrient content of the enriched substrate, furnishing essential elements conducive to robust plant development.

Moreover, the application of ozonated water demonstrated a substantial impact on plant growth for both enriched and unenriched substrates. On average, plants irrigated with ozonated water exhibited lengths of 46 cm and 41 cm for enriched and unenriched substrates, respectively. In contrast, plants irrigated with untreated water displayed shorter lengths, measuring only 38 cm and 33 cm for enriched and unenriched substrates, respectively.

The comparison of different treatment groups, conducted using the Tukey test with a significance level of $p = 0.05$, reveals significant results. Plants grown in the enriched substrate (10%) exhibit significantly longer stems than those grown in unenriched conditions (0%) ($p = 0.000$). Additionally, the positive effect of ozonated water on stem length is particularly pronounced in nutrient-limited environments (0%) compared to nutrient-rich conditions (10%) ($p = 0.033$). These findings suggest that nutrient-rich conditions promote superior plant growth, while ozonated water plays a more compensatory role in nutrient-limited environments.

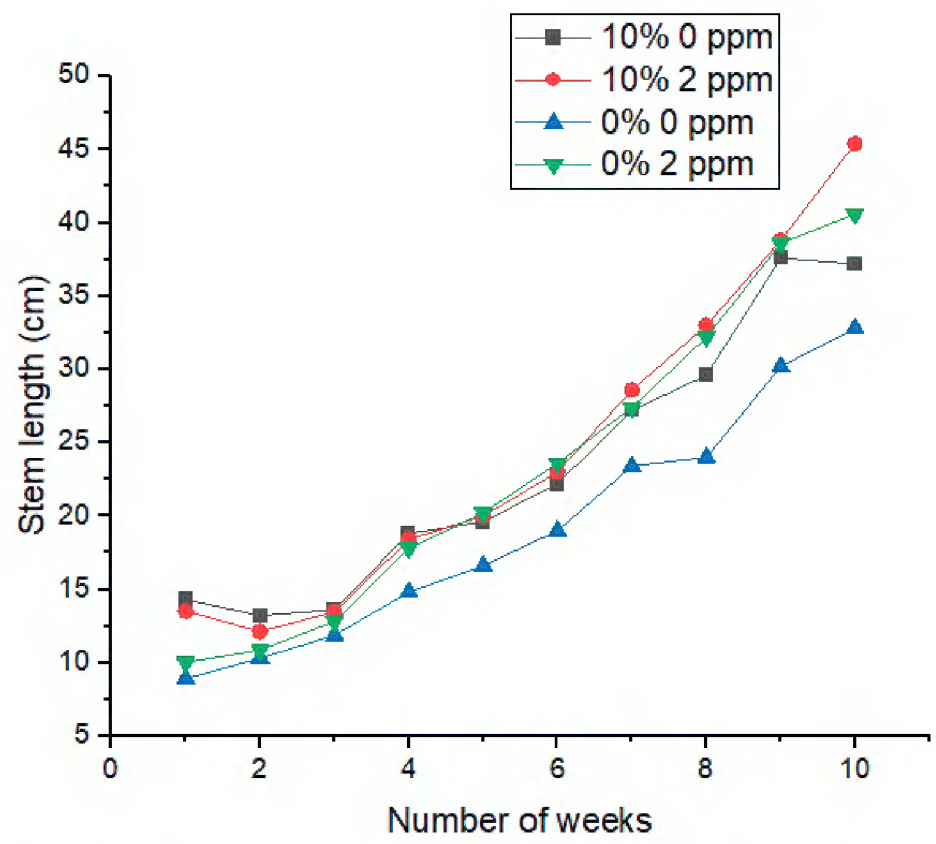

Figure 2. Evolution of the stem length of tomato plants irrigated with ozonated and non-ozonated water in the case of enriched (10%) and unenriched substrates (0%).

The findings regarding stem thickness evolution, as depicted in Fig. 3, underscore the substantial impact of ozonated water irrigation, particularly in the context of unenriched substrate conditions. The graph portrays a consistent increase in stem thickness over time across all treatment groups for tomato plants. An initial ANOVA analysis indicated a significant effect of treatment on stem thickness ($p = 0.029 < 0.05$). Further investigation using the Tukey test revealed specific differences among treatment groups. Comparing plants cultivated in enriched (10%) versus unenriched (0%) substrates unveiled a consistent trend, with plants in the enriched substrate displaying significantly thicker stems throughout the study duration ($p < 0.05$, $p = 0.001$). This disparity is attributed to the enriched substrate's higher nutrient content, crucial for fostering robust

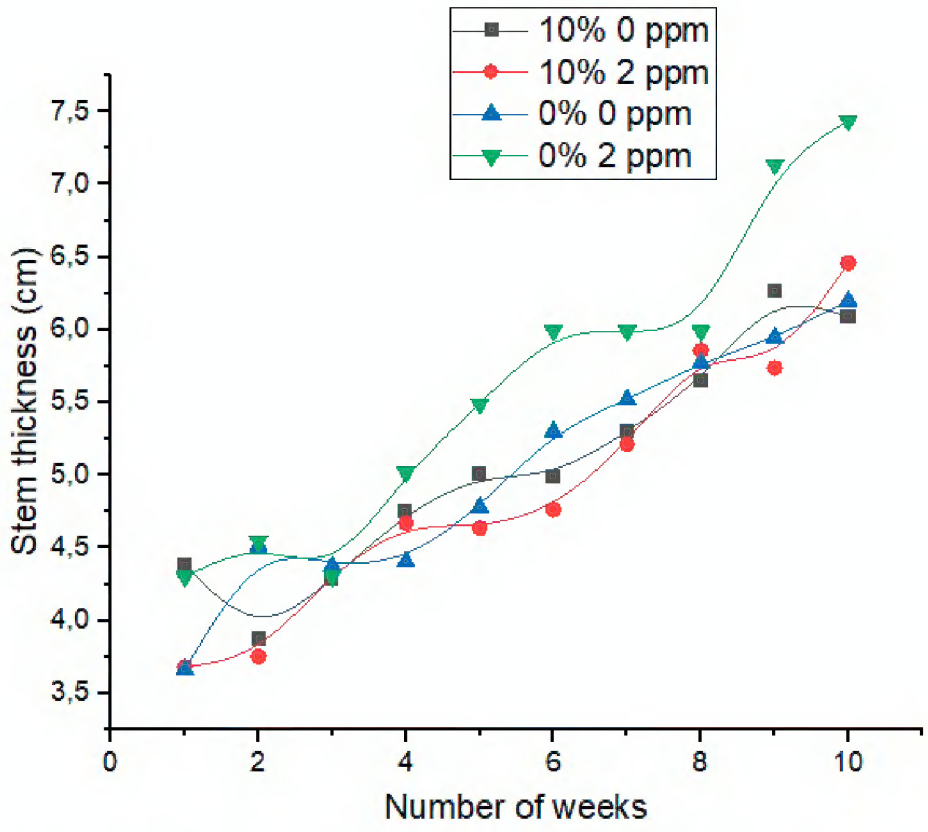

Figure 3. Evolution of the stem thickness of tomato plants irrigated with ozonated and non-ozonated water in the case of enriched (10%) and unenriched substrates (0%).

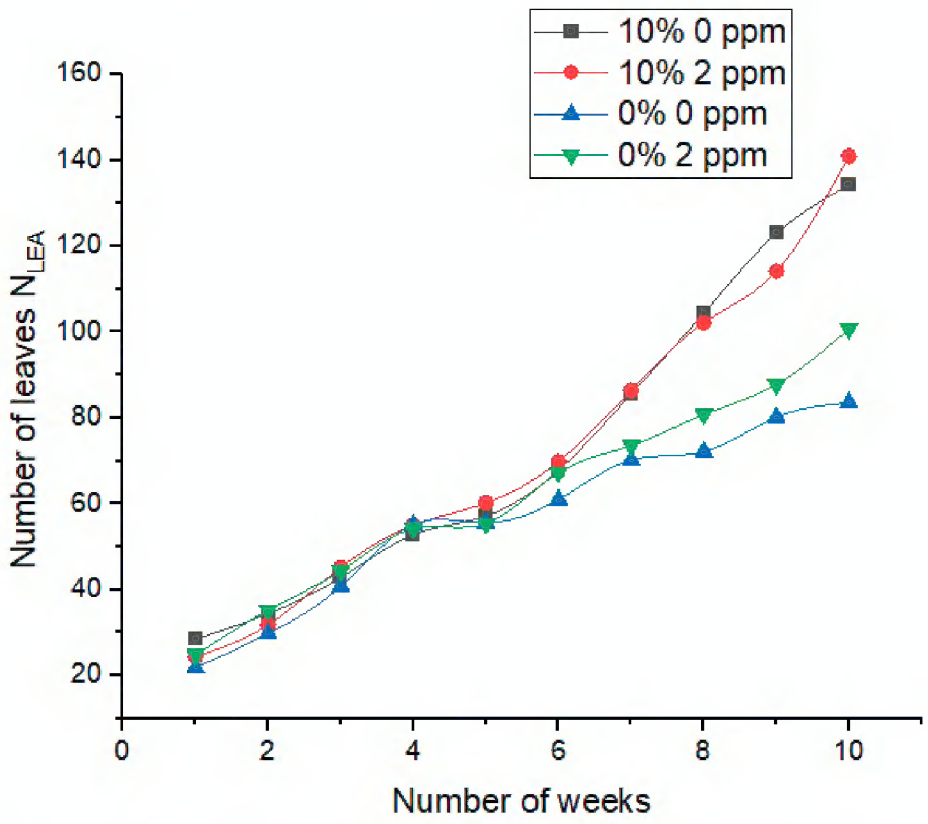

Figure 4. Evolution of the number of leaves of tomato plants irrigated with ozonated and non-ozonated water in the case of enriched (10%) and unenriched substrates (0%).

plant growth. Moreover, a notable distinction was observed between plants irrigated with ozonated and non-ozonated water, particularly in the unenriched substrate ($p < 0.05$, $p = 0.029$). Post week 10, plants irrigated with ozonated water exhibited thicker stems, averaging 7.5 mm compared to 6.1 mm for those receiving non-ozonated water. Interestingly, within the enriched substrate, no significant difference in stem thickness was discerned between plants irrigated with ozonated versus non-ozonated water ($p > 0.05$). This implies that the positive effect of ozonated water on stem thickness may be overshadowed by the abundance of nutrients in the enriched substrate. In summary, both ANOVA and Tukey tests corroborate that ozonated water irrigation has the potential to enhance stem thickness in tomato plants, especially under nutrient-limited conditions.

The analysis of leaf number evolution, as depicted in Fig. 4, reveals significant differences between the two substrates, as indicated by both ANOVA and Tukey tests. ANOVA revealed a significant effect of substrate on leaf number ($p < 0.05$, $p = 1.45e\text{-}06$), with the enriched substrate showing a substantial increase in leaf number, approximately 40% higher compared to the unenriched substrate. Additionally, the Tukey test highlighted specific differences among treatment groups. For instance, plants irrigated with ozonated water in the unenriched substrate exhibited significantly higher leaf numbers (100 leaves) than those irrigated with untreated water (83 leaves) ($p < 0.05$, $p = 0.006$). These findings underscore the beneficial impact of ozonated water, especially in nutrient-limited conditions, as further supported by subsequent results regarding tomato yield.

Analysis of the root development

Fig. 5 illustrates root lengths for three substrate types (10%, 20%, and 40% compost) and varying ozone concentrations (0, 1, 2, and 3 ppm). The ANOVA test revealed a significant difference among the substrates ($p = 0.03$), indicating varying root lengths depending on the substrate type. Despite this statistically significant difference, we observed that root lengths of plants irrigated with ozonated water were greater than those irrigated with untreated water. To validate these findings, a Tukey test was conducted, revealing a significant difference in root length between plants irrigated with ozonated water and those irrigated with untreated water ($p = 0.004$). These results suggest that ozone irrigation has a beneficial effect on root length, irrespective of the substrate type used.

Moreover, the findings delineating the variations in aerial and root mass, depicted in Figs 6, 7 respectively, underscore a substantial influence when plants are subjected to ozonated water irrigation. ANOVA analysis elucidated a statistically significant impact ($p = 0.035$ for Fig. 5 and $p =$

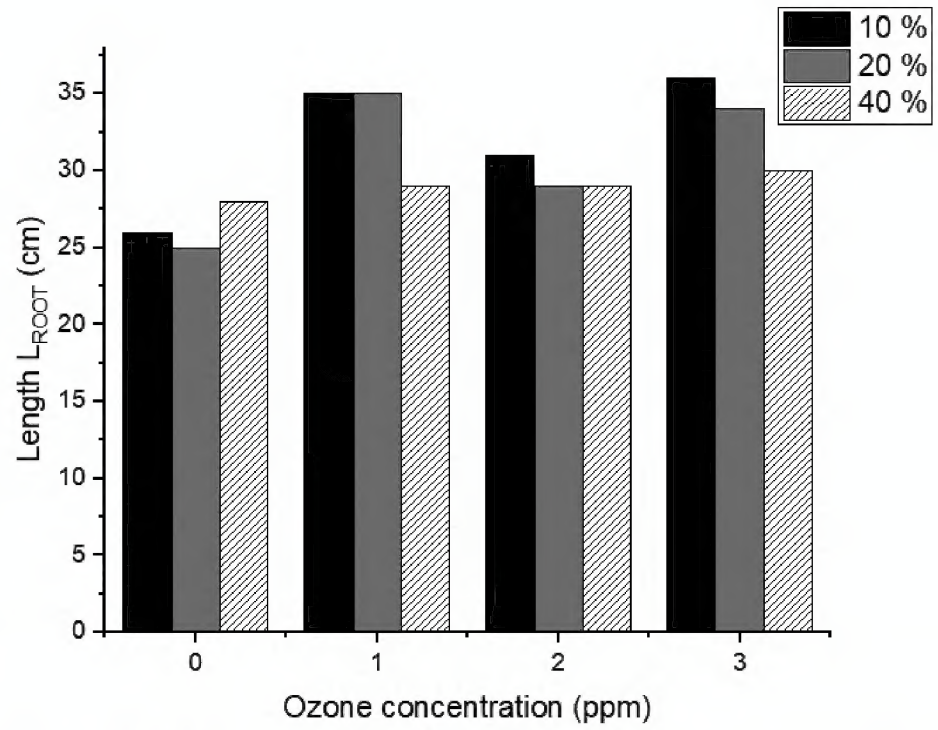

Figure 5. Comparison of the root stem length for the 3 types of soil (compost 10%, 20% and 40%) and different concentrations of ozone (0, 1, 2 and 3 ppm).

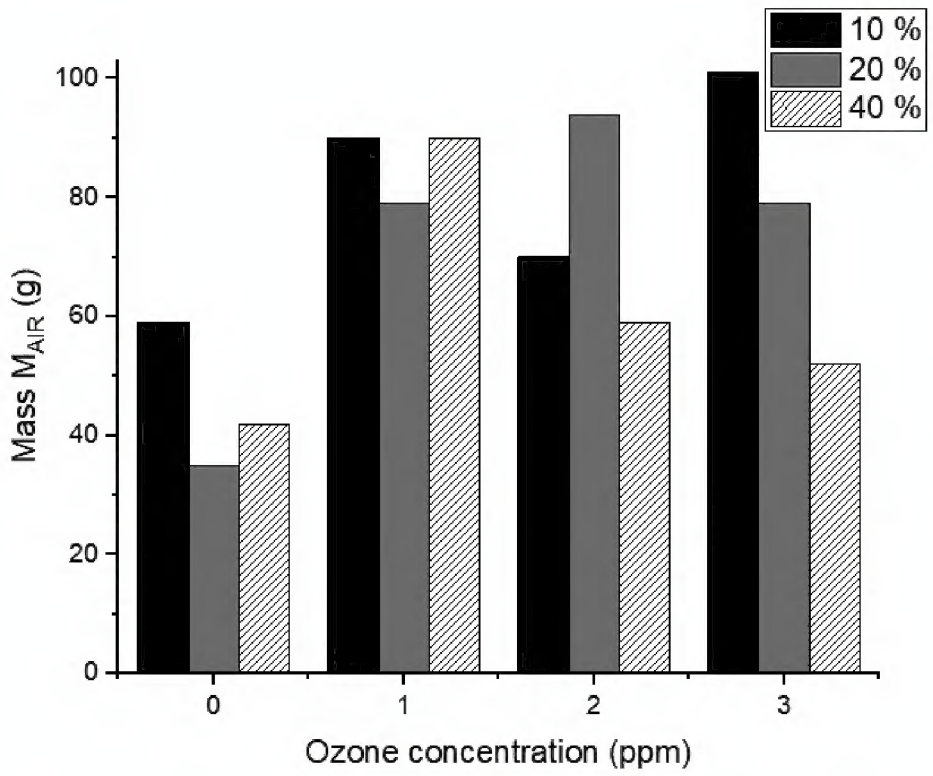

Figure 6. Comparison of the aerial mass of the plants for the 3 types of soil (compost 10%, 20% and 40%) and different concentrations of ozone (0, 1, 2 and 3 ppm).

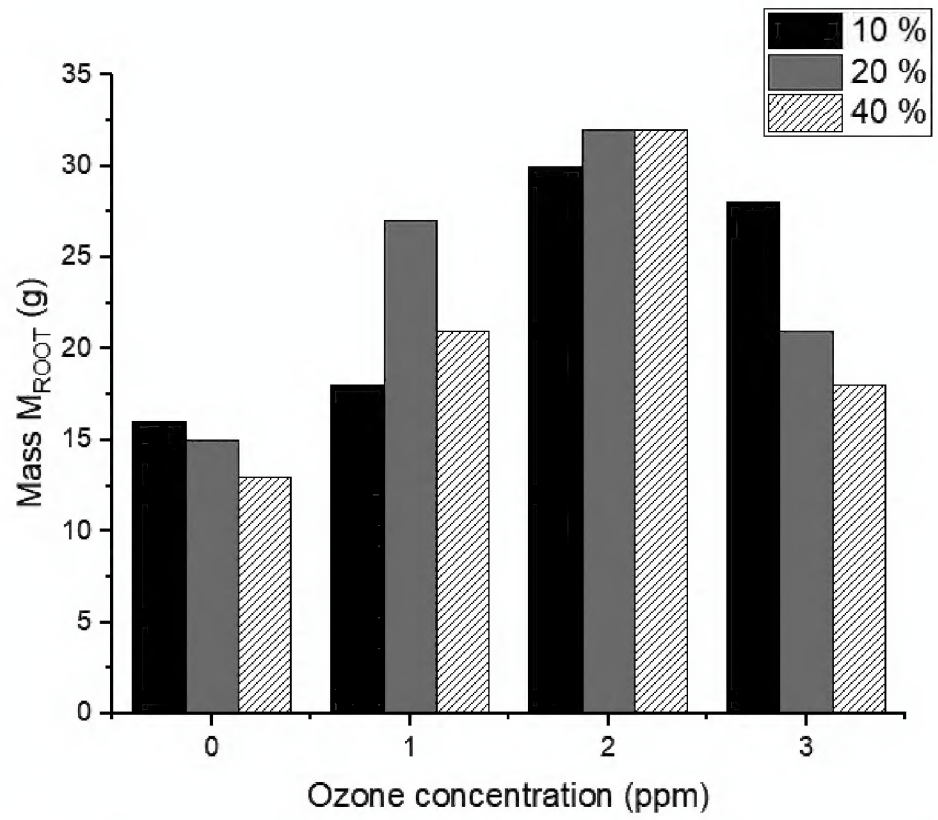

Figure 7. Comparison of the root mass of the plants for the 3 types of soil (compost 10%, 20% and 40%) and different concentrations of ozone (0, 1, 2 and 3 ppm).

0.032 for Fig. 6) on both aerial and root mass attributable to ozone irrigation. Specifically, root development demonstrates a pronounced enhancement, particularly evident at a concentration of 2 ppm, as corroborated by the Tukey test ($p = 0.025$ for Fig. 6 and $p = 0.029$ for Fig. 7), thus fortifying the overall vigor of the plants.

Fig. 8 presents a visual comparison of the aerial and root structures between control plants and those subjected to ozonated water irrigation (2 ppm and 3 ppm).

In terms of root development, the control plant's root is roughly 30% smaller than the root treated with 3 ppm ozone and approximately 50% smaller than the root exposed to 2 ppm ozone. This stark contrast visually highlights the positive impact of ozonated water, particularly at the 2 ppm concentration, on root growth.

Moving to the aerial part, the plant treated with 2 ppm ozone stands out as the largest and healthiest among the three. It boasts a remarkable abundance of green and robust leaves, surpassing the 3 ppm-treated plant by 20% and outperforming the control plant by an impressive 50%. This disparity underscores the evident benefits of ozonated water irrigation, specifically at the 2 ppm concentration, in promoting vigorous aerial development and overall plant health.

Analysis of number of tomatoes

In this section, the focus shifts to the tomato yield, examining the overall harvest across all 15 pots in the row (refer to Fig. 9). The results unveil a substantial enhancement in tomato yield with ozonated water irrigation, reaching its zenith at a 2 ppm ozone concentration. To provide a clearer perspective, consider that in the case of the unenriched substrate, where the yield stands at 13 tomatoes with non-ozonated water, the application of ozonated water resulted in an impressive yield of 30 tomatoes. The most promising outcomes were observed with the 10% substrate under a 2 ppm ozone concentration.

Moreover, when dissecting the three "soil-compost" mixtures, it becomes evident that the optimum configuration involves soil enriched with 10% compost, resulting in a modest boost in productivity with ozonated water. It is noteworthy that the differentiation between the three compositions becomes more accentuated when irrigating with non-ozonated water; the yield with the 10% substrate surpasses that of the unenriched soil (25 tomatoes compared to 13).

As a result, these findings suggest that with ozone application, the necessity for organic fertilization diminishes. The productivity achieved with unfertilized soil, yet irrigated with ozonated water, equals or even surpasses that of fertilized soil. These results underscore the potential of ozonated water as a standalone contributor to enhanced agricultural productivity.

The significant effects of ozonated water on tomato plants indicate that O_3 can increase the growth and quality of tomatoes. The organic fertilization (compost) was able to improve the growth and quality of the tomatoes. In addition, irrigation with ozonated water ensures disinfected water for the plants and allowed a significant increase in the tomato productivity, dry weight of the aerial and root part, and the thickness of the stem.

Irrigation with ozonated water disinfects the roots, improves the soil structure and increases the aeration rate of the soil thus preventing the occurrence of diseases caused by *Fusarium* fungi or bacteria, the bacterial rot or *Phytophthora*.

Physico-chemical analysis

Based on the summarized physico-chemical analysis in Table 2, it can be inferred that, except for the increased total sugars, the majority of parameters remained relatively stable between the ozonated and non-ozonated tomatoes. Irrigation with ozonated water led to improved tomato yield while maintaining consistent parameters. Notably, the enhanced

Figure 8. Aspects of the aerial part (**a**) and the root body (**b**).

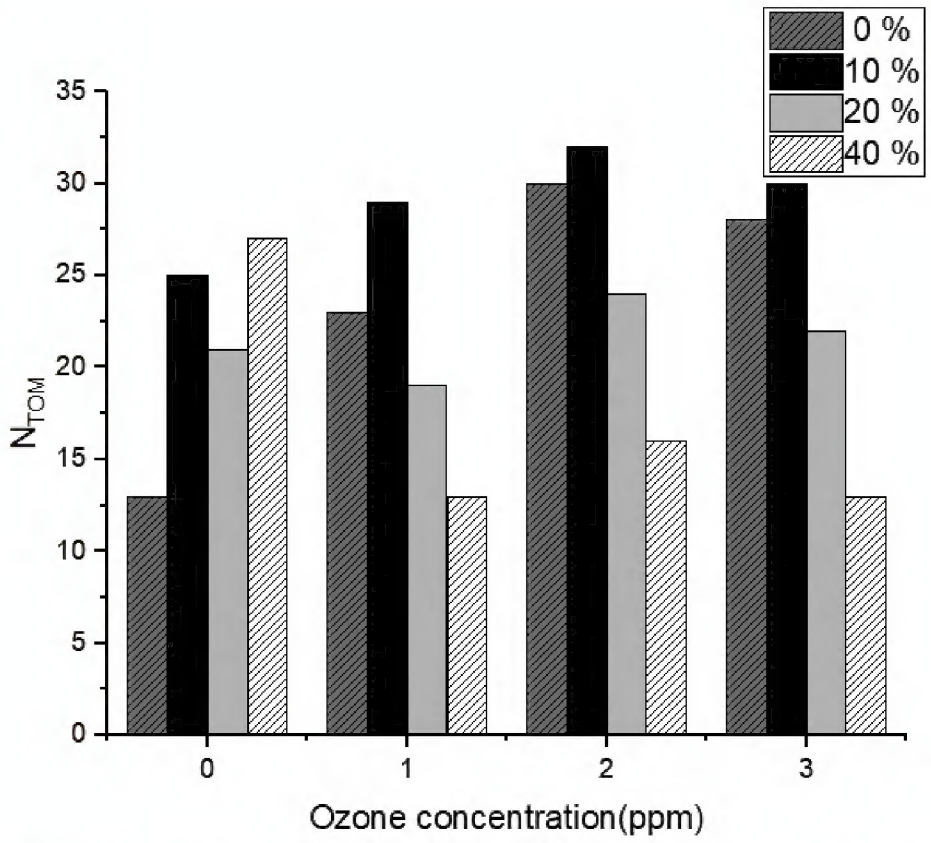

Figure 9. Comparison of the number of tomatoes for the 4 types of soil (compost 0%, 10%, 20% and 40%) and different concentrations of ozone (0, 1, 2 and 3 ppm).

quality of the tomatoes, evidenced by the increase in total sugars, was further confirmed through taste testing. Comparing ozonated and non-ozonated tomatoes reveals distinct characteristics: ozonated tomatoes boast higher total sugar content (7.00% versus 6.50%) and titratable acidity (0.65% versus 0.50%), imparting a sweeter and more tangy flavor. Additionally, they exhibit lower carbohydrate content (5.10% versus 4.61%), potentially contributing to a firmer texture and more satisfying eating experience. In terms of nutrition, ozonated tomatoes marginally outperform non-ozonated ones, showing slightly higher protein content (1.50% versus 1.45%), suggesting slightly greater nutritional value.

Comparative analysis

When comparing our findings with prior research, Martinez-Sanchez and Aguayo (2019) demonstrated a positive correlation between ozonated water and seedling quality, aligning well with our observations regarding the impact of ozonated water on various plant growth parameters. Additionally, Peykanpour et al. (2016) investigated the interactive effects of salinity and ozonated water on cucumber yield components, providing additional insights into the potential benefits of ozonated water in agricultural settings. Furthermore, Ruiz-Espin et al. (2022)

Table 2. Physico-chemical analysis of the tomatoes irrigated with ozonated and non-ozonated water.

Parameter	Reference Method	Ozonated tomato	Non-ozonated tomato
Preparation of the sample	**AOAC 920-149**	/	
pH at 20 °C	NA 751/1990	4.55	4.62
Total soluble solids (TSS)	AOAC 932-12	7.00%	6.50%
Water content	Steaming at 105 °C	91.89%	91.79%
Ash content	AOAC 940-26	0.92%	0.85%
Titratable acidity (TA)	AOAC 942-15	0.65%	0.50%
Protein	AOAC 920-152	1.50%	1.45%
Glucide	G.Bertrand	4.61%	5.10%
Lipid	ISO 4048/2008	0.47%	0.45%
Total sugars	G. G.Bertrand	4.55%	4.19%
Iron	NF EN 14082/2003	1.40 mg/100gr	1.50 mg/100gr
Magnesium	//	7.67 mg/100gr	7.80 mg/100gr
Calcium	Chemical codex	4.73 mg/100gr	4.64 mg/100gr
Energy value	Calcul	29.95 Kcal /100 gr	30.25 Kcal /100 gr
Vitamin C	NF VO3-135 12/2011 (HPLC)	16.29 mg/100gr	16.80 mg/100gr
Provitamin A	NF V18-802 04/2016 (HPLC)	751.0 µg/100 gr	766.0 µg/100 gr
B Carotene	ISO 23443 (HPLC)	594.0 µg /100gr	608.0 µg/100 gr
Aspect	Exam visuel	Raw cherry tomato	
Color	Exam visuel	Red	

explored the physiological and nutritional responses to ozone application in tomato seedling plants, contributing valuable information to our understanding of ozone's effects on plant development. Conversely, the study by Xu et al. (2021) focused on the effects of ozone water irrigation and spraying on the physiological characteristics and gene expression of tomato seedlings, which, while informative, may not directly correlate with our investigation on tomato growth under ozonated water irrigation. Nevertheless, our study adds to the expanding body of literature elucidating the advantageous effects of ozonated water and substrate composition on overall plant development and productivity.

Economic viability assessment

The study highlights the agronomic and environmental implications of using ozonated water irrigation and organic fertilizers in tomato cultivation, particularly in poor soils. Ozonated water significantly improves plant growth and yield, especially in nutrient-deficient soils, while organic fertilizers, like compost, enhance soil quality and plant performance. These practices offer potential benefits such as reduced reliance on pesticides and chemicals, improved water quality, and soil health. However, challenges remain regarding availability, cost, and proper management practices. Further research is needed to fully assess their feasibility and effectiveness in diverse agricultural settings.

Conclusion

This study underscores the significant potential of ozonated water irrigation in bolstering tomato growth and vitality, particularly in nutrient-deficient environments. The synergistic effect between ozonated water and organic fertilization enhances tomato growth and yield, showcasing the promising role of ozone in sustainable agricultural practices. Despite minimal physicochemical alterations, the visible improvements in plant vigor underscore the positive impact of ozone irrigation.

Future research should delve into long-term effects of ozonated water on crop health and soil quality, optimize ozone concentration and irrigation practices for different soil types and crops, explore ecological impacts on soil microbial communities, and integrate advanced technologies for real-time monitoring and precision agriculture. These endeavors will further elucidate ozone's role in sustainable agriculture and pave the way for enhanced crop production and environmental stewardship.

Acknowledgement

This study was performed under the framework of 'Projet Impact Socio-Economique' Contract N° 362 funded by the General Directorate of Algerian Scientific Research (DGRSDT). Moreover, we would like to thank very much the company SODEA (Groupe-Hasnaoui) in which the present study was carried out.

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